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in Deep Boreholes

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DISPOSITION OF PLUTONIUM IN DEEP BOREHOLES*

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KEYWORDS

deep boreholes
direct disposal
excess weapon plutonium
immobilized plutonium
plutonium disposition

ABSTRACT

Substantial inventories of excess plutonium are expected to result from dismantlement of U. S. and Russian nuclear weapons. Disposition of this material should be a high priority in both countries. A variety of disposition options are under consideration. One option is to place the plutonium either directly or in an immobilized form at the bottom of a deep borehole that is then sealed. Deep-borehole disposition involves placing plutonium several kilometers deep into old, stable, rock formations that have negligible free water present. Containment assurance is based on the presence of ancient groundwater indicating lack of migration and communication with the biosphere. Recovery would be extremely difficult (costly) and impossible to accomplish clandestinely.

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INTRODUCTION

As a result of recent changes throughout the world, a substantial inventory of excess separated plutonium is expected to result from dismantlement of U.S. nuclear weapons. The safe and secure management and eventual disposition of this plutonium, and of a similar inventory in Russia, are a high national priority.

A variety of options are under consideration for disposition of this material. These options can be broadly categorized in two groups: (1) utilization as an energy source followed by geological disposal and (2) non-utilization followed by geological disposal. The utilization options have in common the generation of reactor spent fuel that would be disposed of in mined geologic repositories that are being developed for commercial reactor spent fuel and high level waste (HLW). Excess weapon plutonium disposed of in this manner would produce a significant amount of energy and subsequently result in spent fuel, that from a safeguarding point of view, would not differ significantly from commercial reactor spent fuel.

Plutonium disposition non-utilization options can be divided into two types: (1) indirect and (2) direct. Indirect plutonium disposition options require physical immobilization of the plutonium in a particular solid material form. By including appropriate amounts of HLW in the immobilized form, the material becomes similar to reactor spent fuel and can be subsequently placed in a mined geological repository. If HLW is not included in the immobilized form, disposition in a deep borehole is being studied. For direct plutonium disposition little or no preparation of the plutonium and no addition of HLW are required. That is, transformation to a particular chemical or physical form may not be required of the end product, thus allowing plutonium metal, oxide, or other compounds to be dispositioned directly. Deep-borehole disposition is being studied both in the U. S. and in Russia. The U. S. National Academy of Sciences recommended further assessment of the deep-borehole option because of its potential for easier, quicker, and less expensive implementation.

The deep-borehole disposition option involves placing excess plutonium several kilometers deep into old stable rock formations with little free water present. The basis for long-term containment is establishment that ancient groundwater is present. Its presence indicates lack of migration and thus no expected communication with the accessible environment until all the plutonium has substantially decayed (about a quarter-million years). Conceptual design studies serve as the basis for assessing the feasibility of deep-borehole disposition, and to allow comparison to other options in a systematic way. Principal issues of concern include regulatory, statutory, and policy considerations and availability of sites with desirable characteristics. The technology for drilling deep holes, characterizing them, emplacing the plutonium, and final sealing of the boreholes appears to be well in hand.

Screening of Disposition Options

Evaluation criteria have been developed to enable a preliminary screening process of the various options for further evaluation. These criteria include: resistance to theft or diversion by unauthorized parties; resistance to retrieval, extraction, and reuse by the host nation; technical viability; compliance with environment, safety, and health standards; cost effectiveness; timeliness; fostering progress and cooperation with

SIICAM

Russia; public and institutional acceptance; and additional benefits. Disposition options, including the deep-borehole option, that survive this preliminary screening process will be more fully analyzed in the future. Excess weapon plutonium exists in various forms and purity. Some of the more pure forms are candidates for disposition in a utilization option such as MOX fuel for power reactors. However, the less pure and more dilute forms may require costly preprocessing making them unsuitable for MOX fuel fabrication. The latter are excellent candidates for the deep-borehole disposition option.

Previous Considerations of Deep Borehole Disposition

Deep-borehole disposition has been considered in recent decades for disposal of both hazardous and radioactive wastes. This method received significant investigation in the 1970s for disposal of HLW including reactor spent fuel. Several limitations of the deep-borehole option for disposal of reactor spent fuel led several nations to drop it in favor of a mined geologic repository. Examination suggests the reasons for rejecting deep-borehole disposal of HLW and reactor spent fuel do not apply to excess weapon plutonium disposition, and as a matter of fact become assets. A brief summary of the issues considered unfavorable for reactor spent fuel that become acceptable for excess weapon plutonium disposition is given in Table 1.

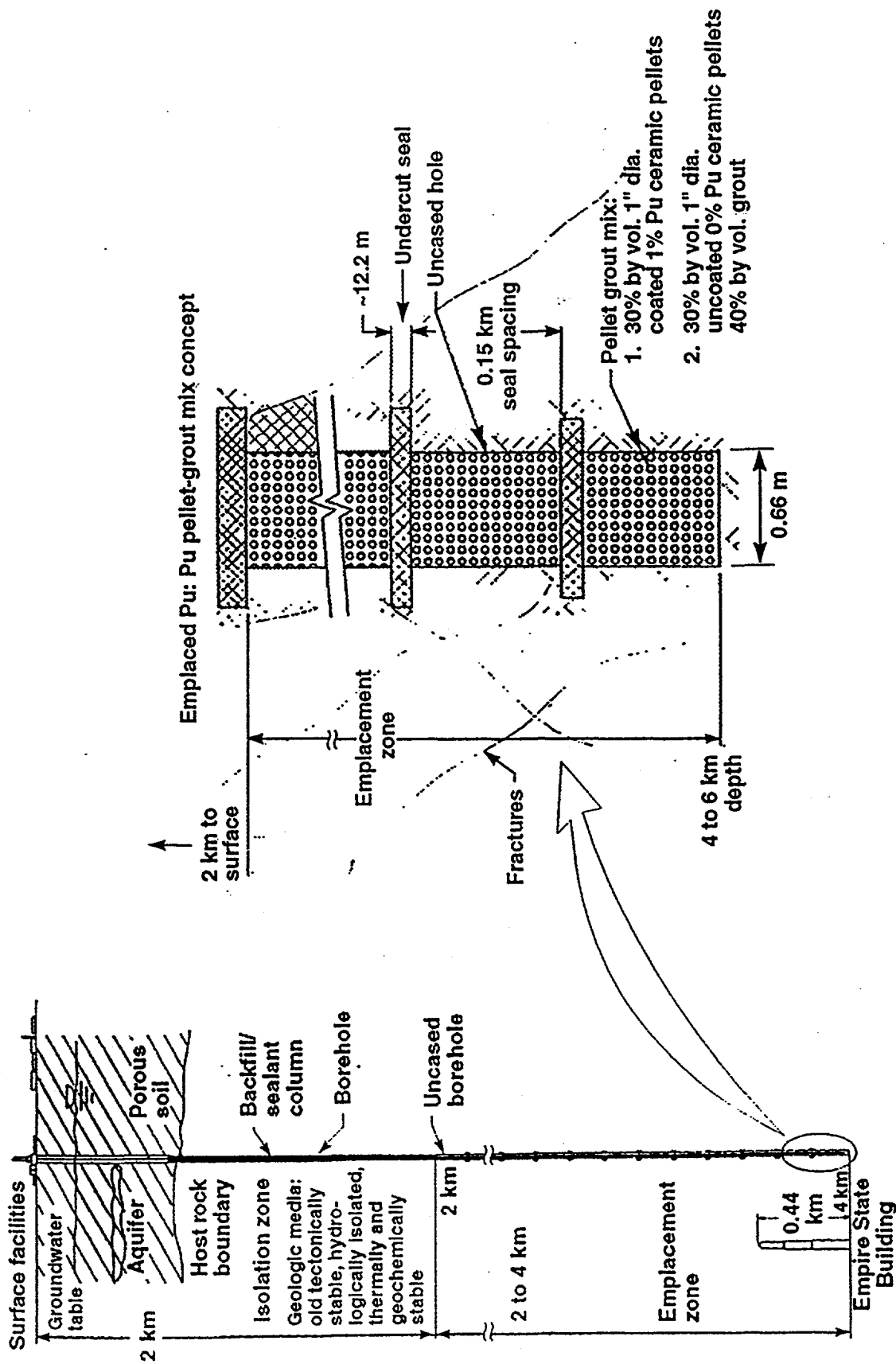
Table 1 Deep borehole differences for commercial reactor spent fuel and plutonium disposition applications.

| Issue | Reactor spent fuel | Plutonium disposition |
|---------------------|--------------------------|-------------------------|
| Retrievability | difficult | difficulty is desirable |
| Volume | large volume, many holes | small volume, few holes |
| Heat generation | limiting | comparatively low |
| Level of isolation | not required | isolation desirable |
| Drilling technology | limited then | greatly improved |

Considerations such as indicated in Table 1, and the desire to explore an option independent from the mined geological repository being considered for reactor spent fuel, have driven the current interest in investigating deep-borehole technology for disposition of excess weapon plutonium.

DESIGN CONFIGURATIONS

Preconceptual design descriptions of the deep-borehole disposition option have been prepared to allow early comparison with other options. These configurations are not site-specific but include descriptions of typical surface facilities, drilling and emplacement facilities, emplacement procedures, and as-emplaced disposition forms. Figure 1 shows a stepped borehole 4 to 6 km deep with plutonium emplacement below a 2-km isolation zone. Arbitrarily, it is assumed that the upper 2 km of deep boreholes would be suitably backfilled with non-fissile material and sealed. Figure 1 also illustrates emplacement of 2.5-cm diameter ceramic pellets containing plutonium



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Figure 1 Conceptual configuration of a deep borehole for disposition of weapon plutonium.

that are grouted into an uncased borehole 0.7 m in diameter at depths of between 2 to 6 km.

Drilling Experience and Technology

Several deep-boreholes have been drilled in recent years. Table 2 lists the characteristics of some of these. These examples indicate that drilling requirements for the deep-borehole disposition option fall within the range of successful experience.

Table 2 Characteristics of actual (relevant) deep boreholes.

| Country | Name of Shaft or Company | Total Depth (TD), km | Dia at TD, m | Rock type | Purpose | Start Date |
|-----------|-----------------------------|-------------------------|--------------------|---|--------------------------|---------------|
| France | FRA-1 Sancerre-Couy | 3.5 | 0.10 | partial crystalline | scientific | ~1987 |
| Germany | KTB Hauptbohrung | 7.5 | 0.31 | diverse crystalline | scientific | 1990 |
| Germany | KTB Vorbohrung | 4.0 | 0.15 | diverse crystalline | scientific | 1987 |
| Russia | Kola | 12.6 | 0.10 | crystalline | scientific | 1970 |
| Sweden | Gravberg-1 | 6.6 | 0.10 | crystalline | petroleum/ scientific | 1986 |
| U.S. (NV) | Mobil 1-A | 6.0 | 0.15 | partial crystalline | petroleum exploration | 1979 |
| U.S. (TX) | Nellie-1 | 5.8 | 0.10 | partial crystalline | petroleum exploration | 1983 |
| U.S. (NM) | Fenton Hill | 4.7 | 0.20 | crystalline overladen by volcanic | scientific | 1979 |
| U.S. (OK) | Haraway 1-27 | 3.8 | 0.15 | crystalline | petroleum exploration | 1981 |
| U.S. (AK) | DOE | 1.9 | 1.4 | andesite | explosive test | 1970 |

The drilling cost of a deep borehole increases more than linearly with its total depth. Drilling cost is not as strong a function of diameter as of depth. For example, with a 2-km isolation depth, one 8-km deep borehole of a given diameter would accommodate as much plutonium as three 4-km boreholes of the same diameter and could cost about the same. The diameter of the less deep boreholes could probably also be greater, thus accommodating more plutonium. The number, diameter, and depth of

deep boreholes reequred for cost-effective disposition of 50,000 kg of excess weapon plutonium has not yet been determined.

Table 3 summarizes the status of deep borehole drilling technology applicable to plutonium disposition. Three classifications of the technology have been used to illustrate the status: (1) standard practice, (2) readily achievable, and (3) the limits of technology. The typical borehole diameter decreases as a function of depth in a step-wise manner. In general, the drilling process starts with a relatively large diameter drill bit down to an interim depth. A casing (metal liner) is inserted into the hole. A cement slurry is then pumped into the casing and up the annulus between the casing and the hole formation. The cemented casing serves several purposes. First, it prevents ground water from entering in the upper portion of the hole. Second, at greater depth it prevents brines from entering the borehole during drilling. Third, it prevents collapse of the hole in the upper regions of the hole where more unstable geology may be found. Finally, it allows the sealing-off of fractured formations that may be encountered. Once the casing is in place, a smaller drill bit is guided through the casing and the hole depth is extended. This procedure can be repeated, resulting in several step-downs in casing size. At some depth, casing the hole is discontinued because it is uneconomical. Table 3 shows that 0.7-m diameter, 4-km deep boreholes are within what is considered to be the technology limit, and these parameters are the bases of current studies.

Table 3 Summary of deep-borehole drilling technology and experience applicable to plutonium disposition.

| Hole Depth, km | Hole Diameter at Total Depth, m | | |
|------------------|---------------------------------|--------------------|------------------|
| | Routine | Readily Achievable | Technology Limit |
| 1.4 ^a | 0.5 | 0.8 | 1.1 |
| 3.0 ^b | 0.4 | 0.7 | 0.9 |
| 4.0 ^b | 0.3 | 0.6 | 0.7 |

^acased

^buncased

Desirable Site Characteristics

Generic site characteristics that would be desirable for a deep borehole have been developed. The primary considerations concern the subsurface emplacement zone, for which desirable characteristics include: long history of tectonic stability, limited open fracture/void space, ancient and preferably conate water presence (if any), sufficient formation thickness for cost-effective emplacement, mechanical strength for hole integrity, gradual thermal gradient and benign geochemistry. Rock types that have been considered include: crystalline/metamorphic "basement" rocks (e.g. granite), tuffs, evaporites (e.g. salt), sedimentary rocks (e.g. shales) and mafic lavas (e.g. basalt). Additional site characteristics of importance include access to transportation, surface water for drilling, reasonable distance from population centers, and a lack of evident geologic resources that could attract future exploitation.

The ability of current technology for remotely determining downhole conditions and material properties is being evaluated. It is expected that an adequate understanding can be obtained through the use of multiple characterization boreholes and extrapolation of existing techniques such as continually-cored sample holes, detailed well logging, and cross-hole testing.

Potential Disposition Forms

A wide range of disposition forms has been considered. Preliminary design examples include plutonium metal, plutonium oxides, and plutonium immobilized in ceramics, glass, or metal alloys. It may also be possible to emplace plutonium-rich residues, scraps, and ash in deep boreholes. No conclusions have as yet been reached on the preferred form option. Direct disposition of plutonium is the simplest option if it proves to be viable. Indirect disposition of immobilized forms has potentially better isolation performance and criticality control. Radionuclides have not been included in the immobilized forms as it is considered unnecessary as a deterrent to diversion from deep borehole disposition. If radionuclides were included, both the radiation and thermal output would needlessly complicate emplacement operations.

Surface Facilities

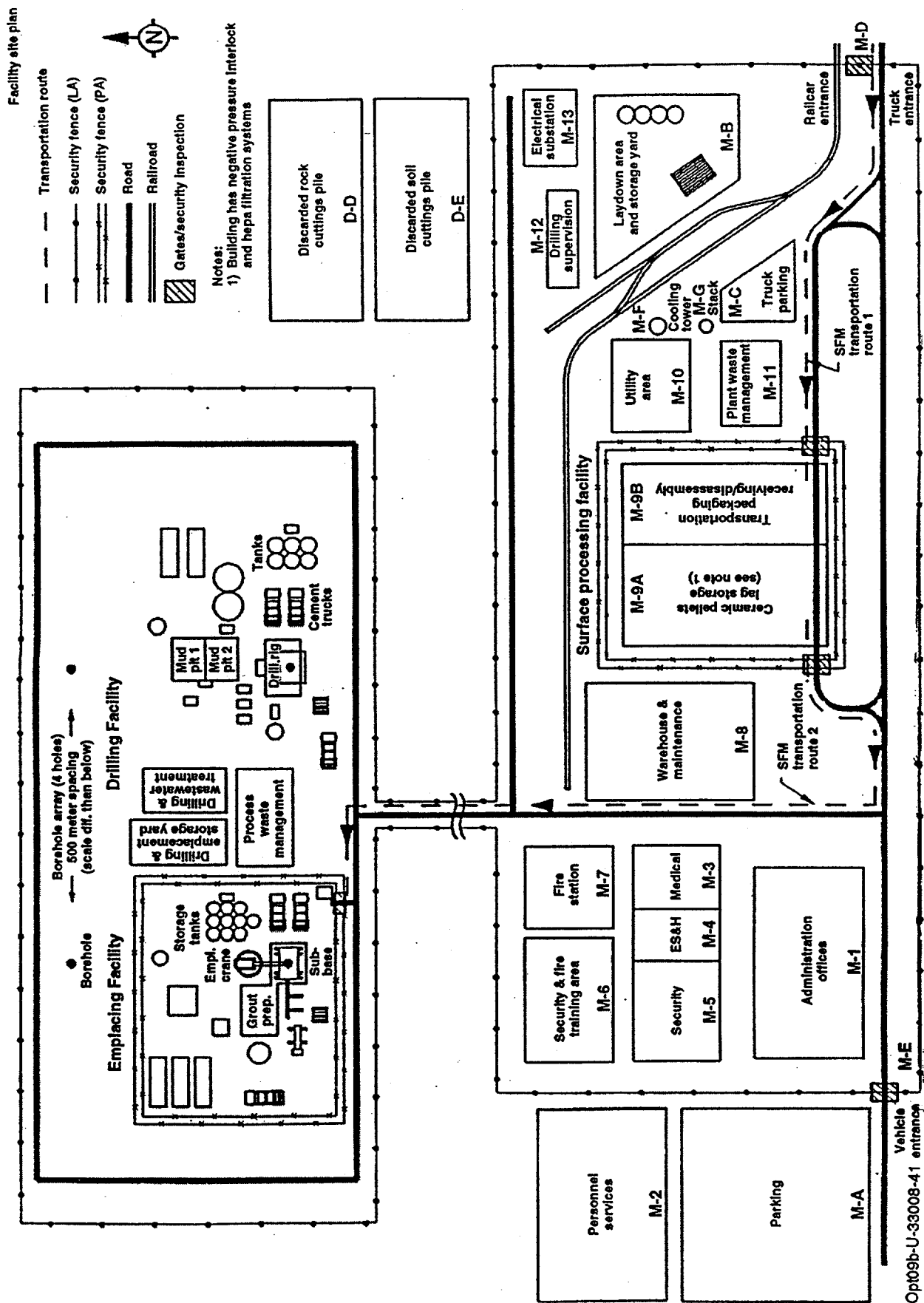
Preliminary surface facility layouts have been prepared that satisfy functional requirements including: receiving plutonium from either rail or truck transport, processing as required, in-process storage, waste management, material security, and operating personnel. Facilities have been sized for disposition of 50,000 kg of plutonium over a 10-year operational period. It is assumed that these plutonium materials would require active security until the borehole is stemmed and sealed. It is also assumed that IAEA safeguards will be applied. Figure 2 is a typical site arrangement plan for such a facility.

Drilling, Emplacement, Stemming, and Sealing

Technology of interest for drilling, emplacement, stemming, and sealing can be found in underground nuclear weapon testing technology, deep geotechnical research drilling programs, and in the mineral exploration industry. Preliminary evaluations suggest that drilling boreholes in suitable rock to depths of 4 to 6 km with usable bottom diameters of 0.5 to 0.7 m can be achieved with reasonable time and cost. Emplacement of canister strings weighing thousands of kilograms can be accomplished with existing equipment. High-integrity seal technology is available from a variety of applications, but detail designs for disposition have not yet been developed.

Number and Size of Deep Boreholes Needed

The number and size of deep boreholes required depends on the form and amount of plutonium that is dispositioned. In general, large diameter holes are not required and the appropriate size may be ~0.7 m at the deepest emplacement point. In addition to other site and cost considerations, the total depth, surface isolation zone, and length of the emplacement zone depend on the insitu geology. Reasonable assumptions for



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Not to scale

Figure 2. Typical surface facility layout for a deep borehole site.

the latter parameters are 4, 2, and 2 km, respectively. With these assumptions, the number of deep-boreholes required to disposition 50,000 kg of excess weapon plutonium can be determined for various forms of the material. Preliminary estimates are given in Table 4.

Table 4 Number of deep boreholes required to disposition 50,000 kg of plutonium. Total depth = 4 km, hole diameter = 0.7 m.

| Disposition Option | Range of plutonium Loading | Potential Number of holes |
|-------------------------------------|------------------------------|---------------------------|
| Direct: | 1-14 (kg/m) | 2-25 |
| • Pu oxide, metal, etc. | | |
| Indirect, Immobilized forms: | 0.25-12 (mass fraction %) | 1-100 |
| • grouted ceramic pellets | | |
| • glass logs | | |
| • ceramic logs | | |
| • metal alloy | | |

SAFETY CONSIDERATIONS

Preliminary safety considerations, both operational and post-operational have been assessed. The unique considerations for deep-borehole disposition are the long-term safety of the emplaced material.

Long Term Plutonium Isolation

Permanent isolation of plutonium in deep boreholes relies primarily on the inherent characteristics of the geologic medium. The emplacement canisters are relied upon only for operations and are not expected to isolate the material from the host rock. It is possible that some immobilized disposition forms would have significant long-term performance in the emplaced environment. If the site has suitable characteristics, by definition, there are no significant natural pathways for radionuclide migration. Isolation demonstration then focuses on the potential for migration upward through the stemmed and sealed borehole and on creation of potential vertical flow pathways in the host rock during drilling, operation, stemming, sealing, or the postclosure thermal transient. The very high lithostatic load in both the host rock and the stemmed borehole at the emplacement depth are expected to inhibit opening of fractures and limit voids significantly. Mobile water (if any) would have a high ionic strength, with a vertical density gradient sufficient to suppress thermal buoyancy. Periodic pressure or undercut seals would be used to interrupt new stress-relief fractures created parallel to

the borehole. These are some of the key processes that would require verification in a characterization program.

Criticality Control

Emplacement of fissile material in a constrained volume, as in the case of the deep borehole, requires attention to the potential for critical configurations. Several approaches are being studied for operational and long-term (postclosure) criticality control. Individual emplacement packages can be designed to contain criticality limited quantities of plutonium. Neutron absorbers can be incorporated into the disposition form and into the packing material surrounding the canisters. Plutonium can be physically dispersed throughout a matrix at concentrations that maintain sub-criticality. Combinations of these approaches are included in current designs. In addition, preliminary studies have considered the potential for reconcentration of plutonium in the geosystem, and whether any adverse consequences would be expected from post-closure criticality. These studies are ongoing.

REGULATORY AND LICENSING ISSUES

Perhaps the greatest current uncertainty in the feasibility of deep-borehole disposition is the regulatory and licensing requirements that might be imposed. Because concentrated fissile material in significant quantities has not been considered for direct disposition before, current waste management regulations are not applicable. Several existing or planned facilities may be useful as relative benchmarks to suggest regulatory stringency, including; the Greater Confinement Disposal Facility (GCDF) at the Nevada Test Site for disposal of gram quantities, the Waste Isolation Pilot Plant (WIPP) being developed for disposal of many tons of defense transuranic wastes near Carlsbad, NM and the High-Level Radioactive Waste repository (Yucca Mountain) designed to emplace much larger quantities of plutonium incorporated in 70,000 MT of reactor spent fuel. WIPP is a useful precedent for developing a custom regulatory environment to assess a deep-borehole facility because the hazard levels are similar and both are unique facilities. The fundamental safety argument for the borehole is emplacement in old stable rock with little, if any, mobile water and no hydraulic communication with accessible water. Some precedent exists for deep injection of hazardous material into waters which do not communicate with accessible waters, and this approach is central to feasibility of deep borehole disposition. Current plans are to initiate dialog with NRC and EPA to consider possible regulation and licensing of such a facility.

CONCLUSION

Disposition of excess weapon plutonium in deep boreholes is currently in a preliminary scoping assessment stage to allow comparison to other disposition options. Initial studies of technical feasibility, potential safety issues, and potential cost and schedule are encouraging. Numerous issues require further assessment, with regulatory implementation being the greatest uncertainty. The possible achievement of criticality in the long term and its effect, should that occur, requires further study.

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Fissile Materials Disposition Program

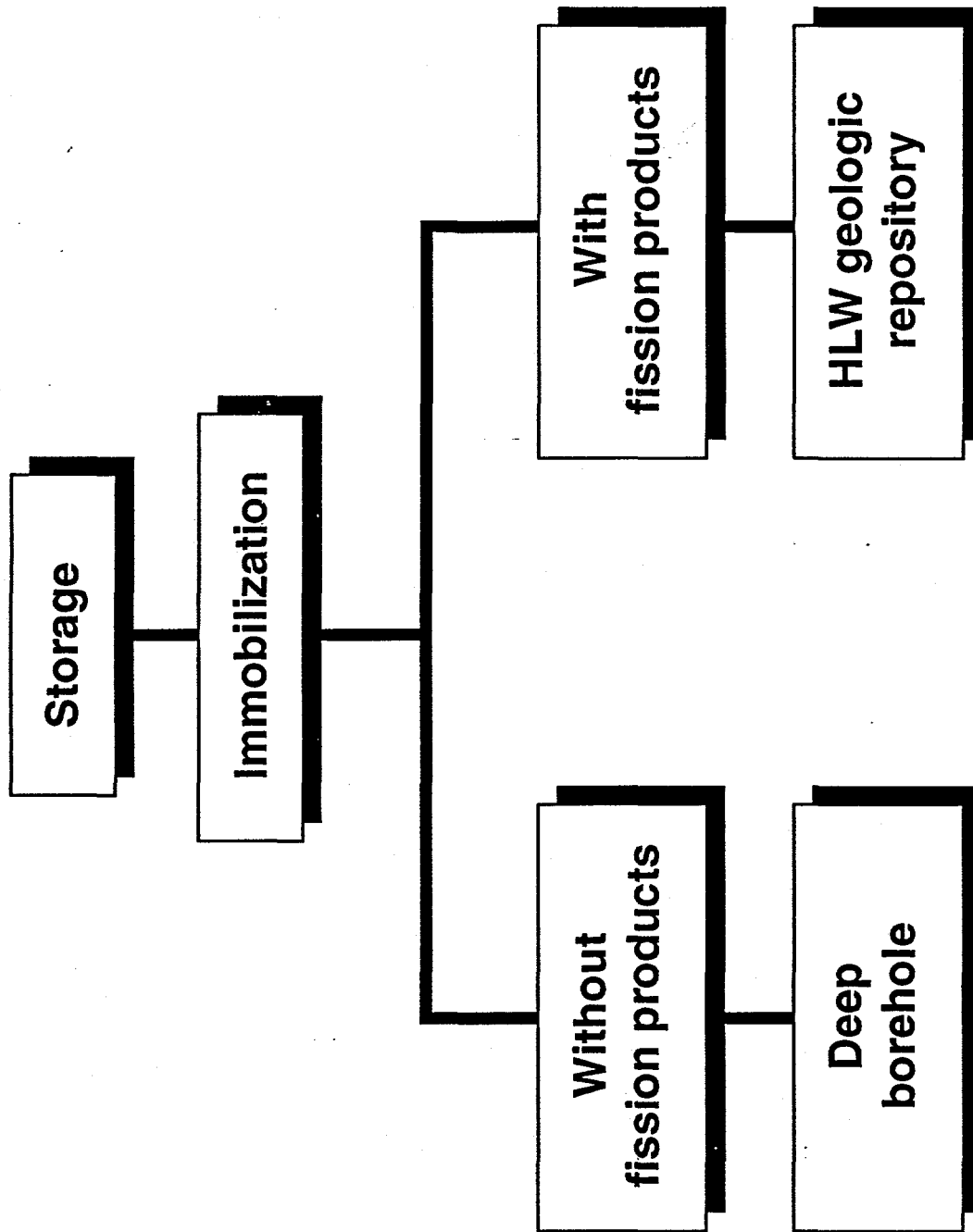
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Presentation Outline

- 1. Deep borehole concept for Pu disposition**
- 2. Technical status**
 - deep borehole experience and limitations
 - anticipated depths, diameters and numbers
 - geotechnical concerns
- 3. Issues**
 - long term performance
 - nuclear criticality
 - U.S. regulatory status
- 4. Future plans**

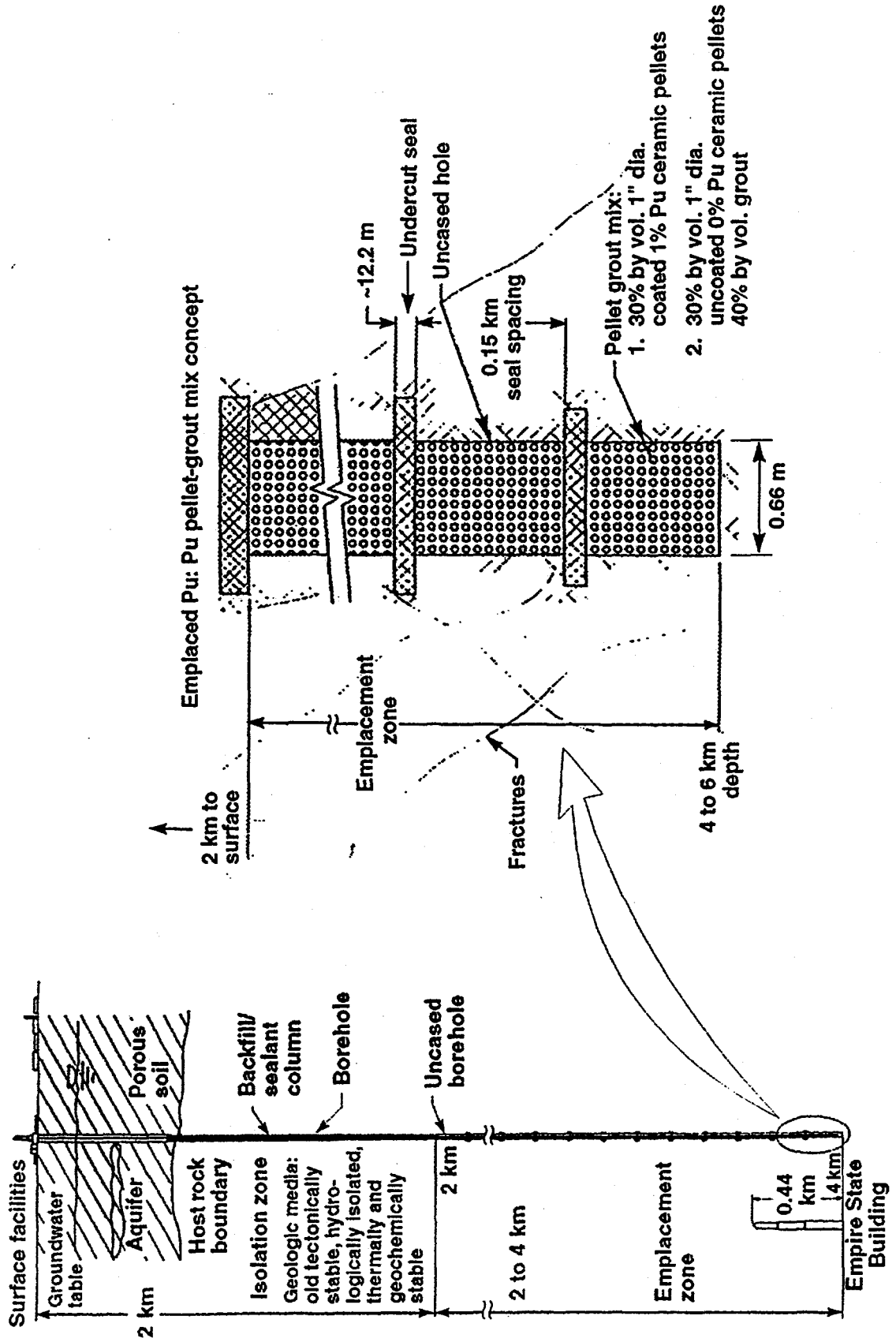
Non-reactor disposition studies for plutonium



How the Deep Borehole works

1. The basic safety argument is permanent isolation in deep, old and stable rock from which water does not communicate with the accessible biosphere.
2. "How deep" depends upon location of desired geologic conditions.
Estimated from 2 to 10 Km below the surface.
3. Design concepts under consideration include:
 - Direct disposal of Pu metal or oxide
 - Disposal of immobilized forms: glass or ceramic
4. Variations range from one large diameter hole to dozens of small diameter holes.

Deep borehole concept for disposition of ceramic immobilized Pu disposal form: emplaced Pu zone



Desirable geologic siting features

- 1. Thick layer of old rock with good mechanical properties for drilling and sealing.**
- 2. Demonstrated geologic history of stability.**
- 3. Little free void space, little water content.**
- 4. Any water present is very old and is not mobile.**
- 5. Any water present is not usable (probably very saline).**
- 6. Large vertical separation distance from usable water.**

Technical Status

- 1. Drilling, emplacement and characterization experience is available from:**
 - (a) nuclear weapons testing**
 - (b) oil, mineral and gas exploration**
 - (c) geoscience research**
- 2. A range of operational design concepts are being considered:**
 - (a) Direct emplacement of as received shipping canisters**
 - (b) Cementation of oxide into emplacement package**
 - (c) Disposal of immobilized forms (i.e. glass logs)**
 - (d) In-situ cementation of immobilized aggregate**
- 3. Drilling and emplacement technology appears to be adequate.**

Characteristics of some relevant deep bore hole experience

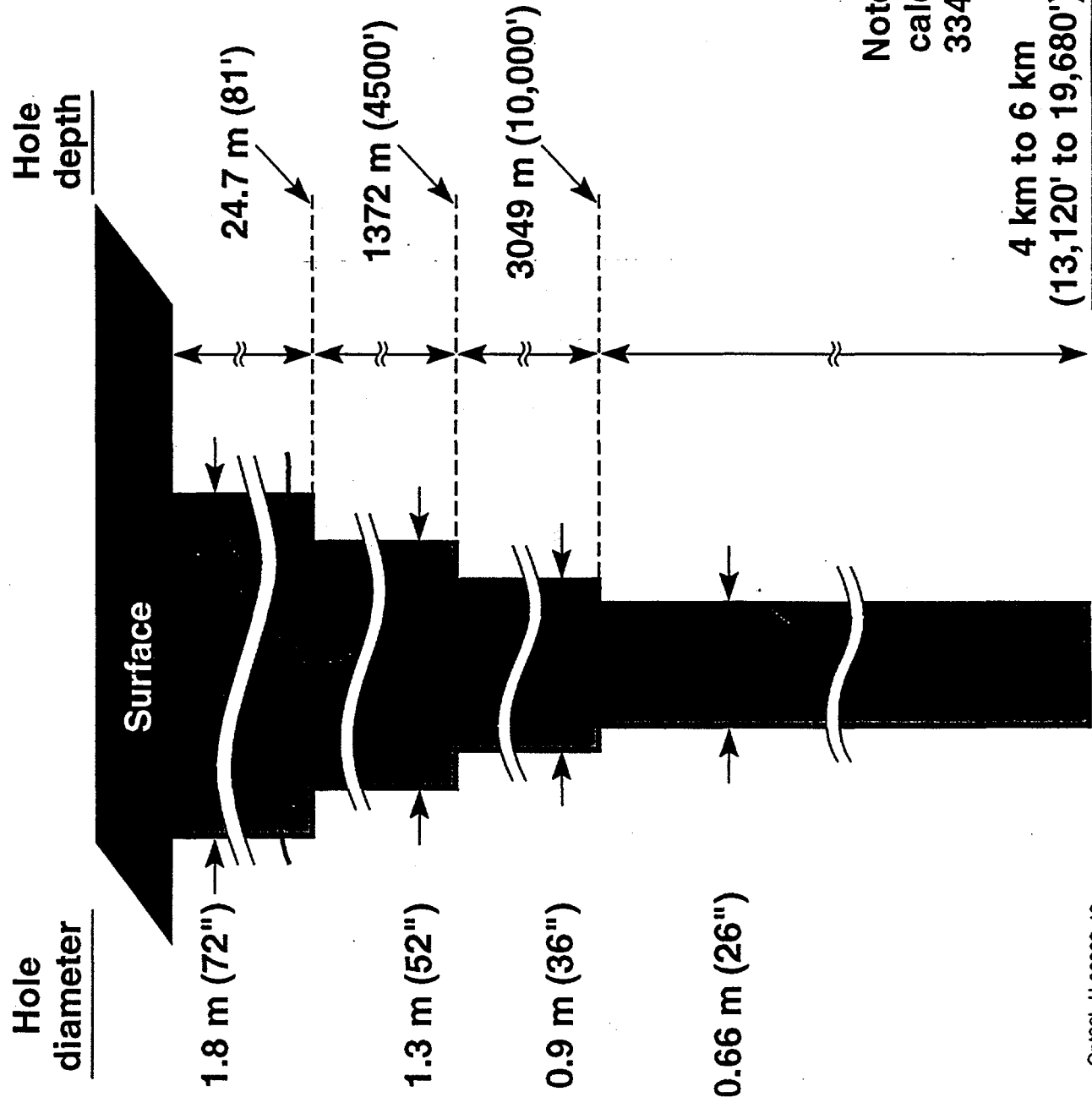


| Country | Name | Total Depth, km | Diameter | | Rock type | Type of well |
|-------------|---------------------|-----------------|----------------|--|----------------------------------|-----------------------|
| | | | total depth, m | | | |
| Germany | KTB Vorbohrung | 4.0 | 0.31 | | Crystalline | Scientific |
| | KTB Hauptbohrung | 7.5 | 0.15 | | (highly diverse) | Scientific |
| U.S. | Mobile 1-A (NV) | 6.0 | 0.15 | | Partial crystalline | Petroleum exploration |
| U.S. | Nellie-1 (TX) | 5.8 | 0.1 | | Partial crystalline | Scientific |
| Japan | JUDGE Project | 12 (planned) | 0.1 | | Subduction zone diverse | Scientific |
| France | FRA-1 Sancerre-Couy | 3.5 | 0.1 | | Partial crystalline | Scientific |
| Switzerland | SWT-1 Nagra Project | 1.5 | 0.1 | | Partial crystalline | Scientific |
| Russia | Kola Borehole | 12.6 | 0.1 | | | Scientific |
| U.S. | Fenton Hill (NM) | 4.7 | 0.2 | | Crystalline overlain by volcanic | Scientific |
| U.S. | Haraway 1-27 (OK) | 3.8 | 0.15 | | Crystalline | Petroleum exploration |

Some other large diameter – deep borehole experience

| Country | Name of shaft or company | Depth (m) | Diameter (m) | Rock type |
|------------------|---|-----------|--------------|---------------------------------|
| Sudbury, Canada | Creighton No. 9 | 2,176 | 6.1 | Norite |
| South Africa | Anglo-American Mine Co. President Steyn No. 4 | 2,317 | 10.2 by 11.0 | Sandstone, volcanics, quartzite |
| South Africa | Elsburg | 1,982 | 11.0 | Sandstone, quartzite |
| U.S. | Henderson Shaft | 610 | 7.3 | Metamorphics |
| South Africa | Welkom Shafts (several) | 2,200 | 6.0 to 8.5 | Quartzite |
| Amchitka, Alaska | U.S. Department of Defense | 1,906 | 2.0 | Andesite |
| New Mexico | Kerr McGee | 450 | 2.0 to 2.5 | Sandstone |
| Nevada | U.S. Department of Energy | 600 | 2.0 to 2.5 | Alluvium, tuff |

Deep bore holes have decreased diameters as depth is increased



Summary of deep borehole drilling technology and experience that can be applied to Pu disposition



| Hole depth | Status of technology: Diameter | | |
|-------------------------------|--------------------------------|--------------------|---------------------|
| | Routine | Readily Achievable | Limit of Technology |
| ^a 1372 m (4500') | 0.5 m (20") | 0.8 (32") | 1.1 m (42") |
| ^b 3050 m (10,000') | 0.44 m (17.5") | 0.7 (28") | 0.9 m (36") |
| ^b 4000 m (13125') | 0.31 (12.2) | 0.56 (22") | 0.66 m (26") |

^aCased

^bUncased

Site related geotechnical status

- 1. Current studies are not site-specific.**
- 2. Desirable site characteristics and criteria for siting are being assessed.**
- 3. It appears potential sites can be found that can satisfy the criteria.**
- 4. Site characterization technology is extensive but may require additional development.**
- 5. Existing knowledge of characteristics of deep stable geology without potential oil or mineral resources is limited.**

Long term performance issues

- 1. Primary reliance is on lack of water flow and transport in the natural system.**
- 2. Understanding of potential flow paths must be developed.**
- 3. Potential for creating new flow pathways during construction and operation must be assessed.**
 - methods for sealing such pathways must be demonstrated**
- 4. Value of migration barriers used to pack and seal the borehole must be demonstrated.**
- 5. Shaft seal integrity for long time periods requires study.**

Nuclear criticality issues

- 1. Placement of significant quantities of fissile material in a evolving natural system raises concerns for long term criticality.**
- 2. Criticality control can be achieved by physical separation of plutonium, neutron absorbers, or a combination of both.**
- 3. Geochemical processes have long term potential to remove and redistribute both Pu and absorbers into surrounding rock.**
- 4. Analyses are in progress to bound conditions for criticality potential and estimate possible effects.**

Regulatory Status

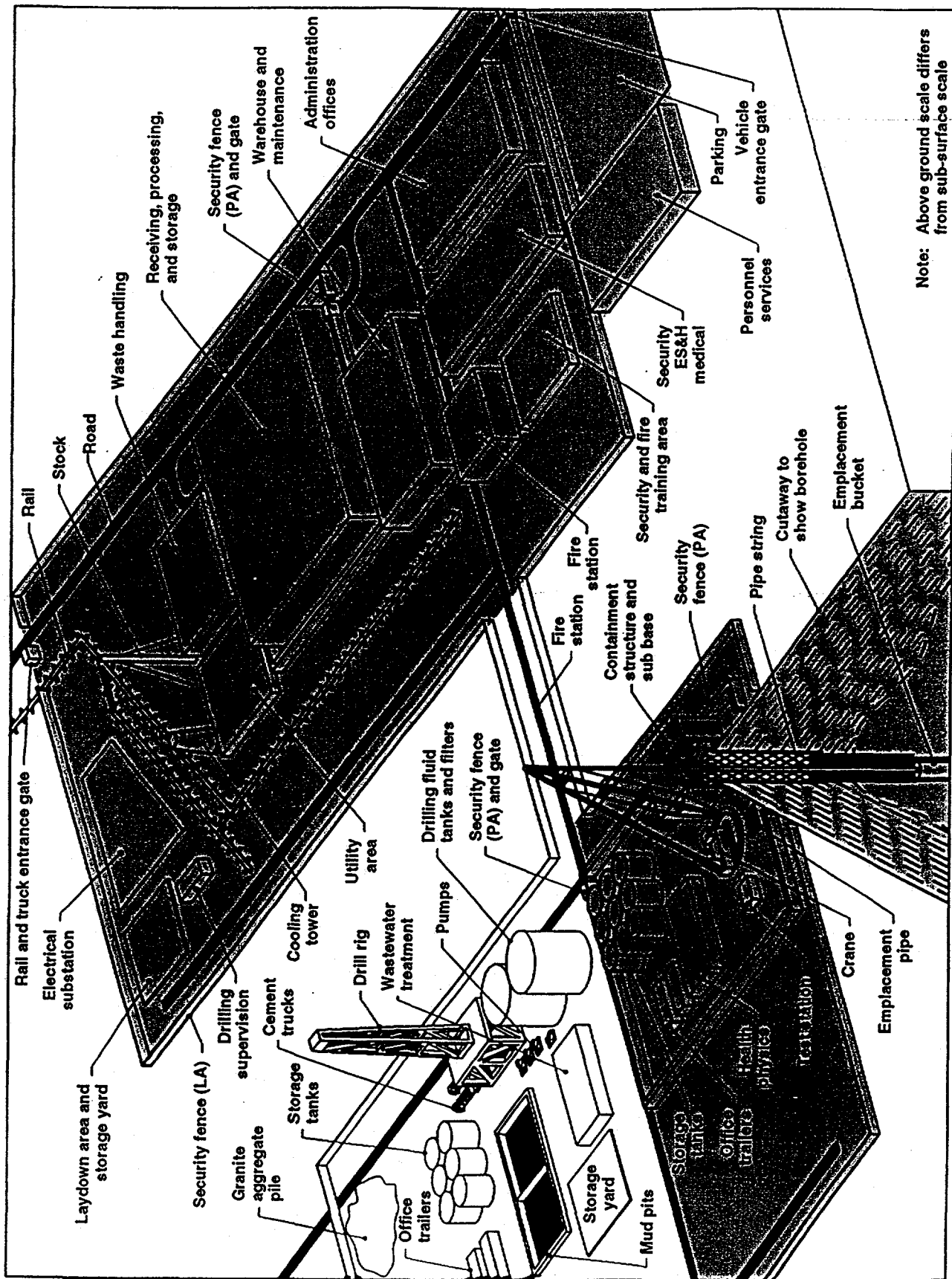
1. Current U.S. regulations are not generally applicable.
 - Concentrated Plutonium was not considered when current regulations were developed.
2. Anticipate development of new regulations which are intermediate between U.S. low level wastes (LLW) and high level wastes (HLW).
3. Nuclear criticality requirements are a significant unknown.

Primary uncertainties are really regulatory and policy issues, not engineering and technical issues.

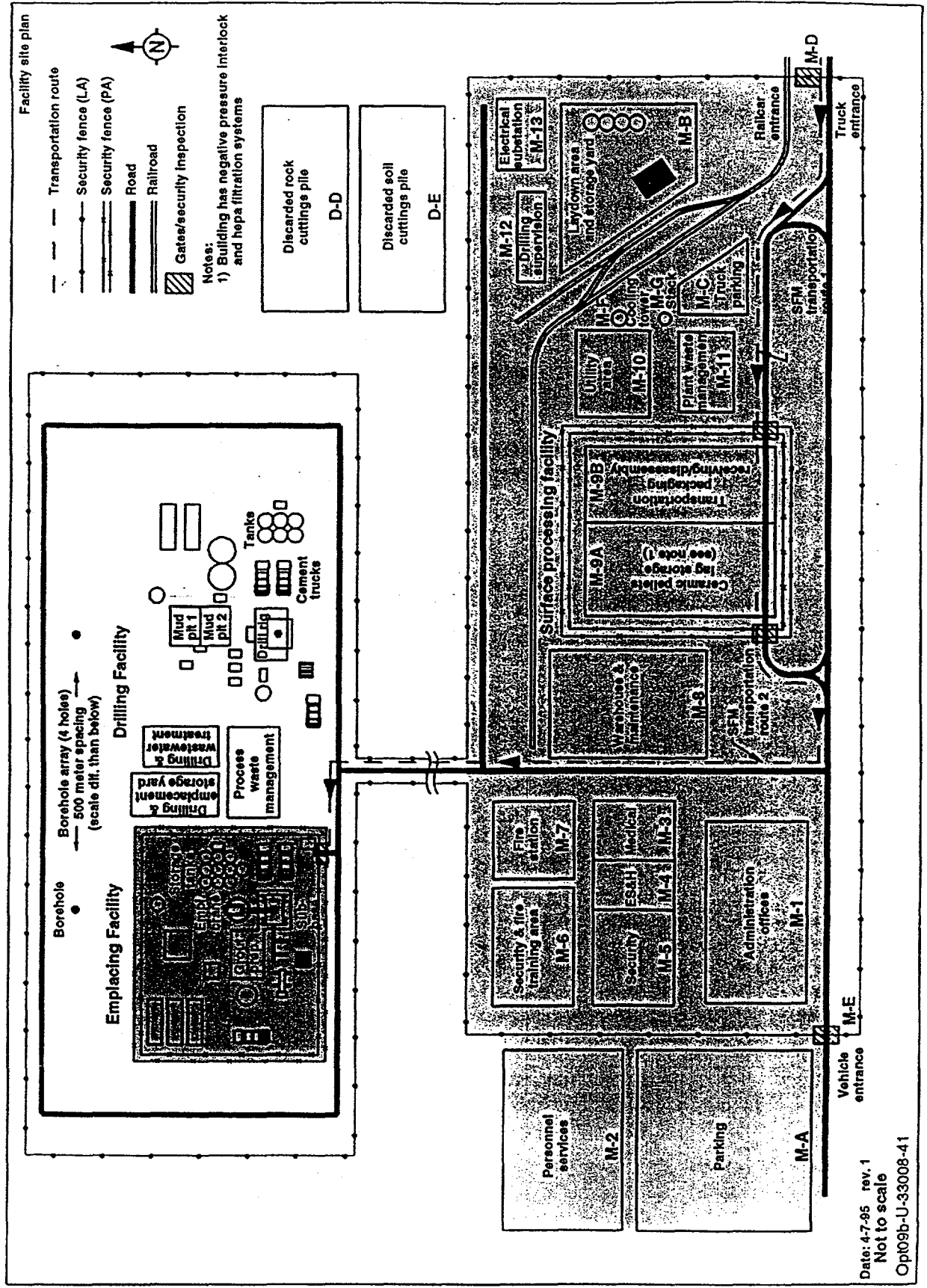
Future Plans

- 1. Develop additional data:**
 - Develop potential regulatory requirements**
 - Prepare conceptual designs**
 - Assess environmental and safety impacts**
- 2. Support those selecting U.S. disposition options:**
 - Assess technical information needs**
 - Prepare design concept implementation plans**
 - Estimate economic costs and schedules**
- 3. Prepare for research, development and testing, if option is selected for further study.**

Deep bore hole Pu disposition facility concept



Deep bore hole facility site plan and SFM transportation routes — immobilized disposal option



Number and characteristics of deep boreholes required to disposition 50 MT of plutonium



| Borehole concept | Pu loading wt% | Hole emplacement length | | |
|---------------------------|-------------------|-------------------------|--------------|-------------|
| | | 4 km | 5 km | 6 km |
| Direct disposal | | | | |
| • Pu oxide, metal, etc. | Varied | 4 | 3 | 2 |
| Immobilized forms: | | | | |
| • Grouted ceramic pellets | 0.5 5 10 | 4 2 1 | 3 2 1 | 2 1 1 |
| • Glass logs | 5 10 | 3 2 | 2 1 | 1 1 |
| • Ceramic logs | 0.5 5 10 | 14 7 3 | 10 5 2 | 7 3 1 |

Site related geotechnical status

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